Assessing the geomorphic response and sensitivity of a Himalayan river to climate change and anthropogenic pressures

Évaluation de la réponse géomorphologique et de la sensibilité d'une rivière himalayenne au changement climatique et aux pressions anthropiques

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RÉSUMÉ

Comprendre la réponse des rivières aux influences externes et leur sensibilité géomorphologique est essentiel à la planification de stratégies de gestion durable. La rivière Yamuna, avec ses 1 376 km de longueur et son bassin hydrographique de 366 223 km², est un fleuve himalayen essentiel qui alimente 341 628 personnes pour leurs besoins agricoles, industriels et urbains. Cette étude intègre la caractérisation géomorphologique, l'analyse de la puissance des cours d'eau, la modélisation hydrologique et la télédétection afin d'évaluer sa réponse aux scénarios climatiques projetés et aux influences anthropiques. L'analyse géomorphologique a été réalisée à l'aide du cadre « River Styles » et l'analyse de segmentation du lit fluvial à l'aide de la boîte à outils Fluvial Corridor.

Les attributs géomorphologiques des « River Styles » ont été analysés à différentes échelles spatiales et ont permis de classer le système fluvial en treize classes géomorphologiques différentes. Les distributions de la puissance des cours d'eau ont été dérivées des relevés hydrologiques historiques et du profil longitudinal dérivé du MNE. Les scénarios hydrologiques futurs ont été simulés via le modèle hydrologique semi-distribué à capacité d'infiltration variable (VIC), piloté par les modèles climatiques INM-CM5-0 et MIROC6. Les résultats révèlent une variabilité spatiale des impacts du changement climatique, classant les tronçons fluviaux en zones sensibles et résilientes. La carte de sensibilité à l'échelle du tronçon du système fluvial de la Yamuna fournira un ensemble de données fondamentales pour prioriser les efforts de gestion des cours d'eau.

De plus, un tronçon de 460 km de long, du front de montagne jusqu'en aval de la mégapole de Delhi, a été analysé grâce à une segmentation haute résolution (500 m) du fleuve à l'aide de la boîte à outils du corridor fluvial afin de comprendre les impacts anthropiques sur le chenal fluvial. Les principaux paramètres géomorphologiques, notamment la largeur du chenal, l'indice de tressage, la largeur de l'eau et la largeur de la végétation, ont été quantifiés pour chaque segment. Les résultats mettent en évidence d'importantes modifications d'origine humaine. Les influences anthropiques, en particulier dans les tronçons alluviaux, ont dépassé les contrôles climatiques et géologiques, entraînant des transformations géomorphologiques. L'extraction de sable, la construction de barrages et l'empiètement dans le corridor urbain de la mégapole de Delhi ont notamment perturbé la dynamique fluviale naturelle.

Cette étude multidisciplinaire à plusieurs échelles met en évidence l'intégration des facteurs climatiques et anthropiques qui façonnent la morphologie contemporaine de la Yamuna et sa trajectoire future. Les résultats apportent de nouvelles perspectives pour des stratégies de gestion intégrées et multi-échelles. La synthèse des projections climatiques, des simulations hydrologiques et des analyses géomorphologiques fournit une évaluation complète de l'évolution de la dynamique fluviale, plaidant en faveur d'interventions proactives pour atténuer les perturbations d'origine humaine et préserver la fonctionnalité des cours d'eau face à des pressions environnementales croissantes.

Keywords- Barrages, Changement climatique, Classification des styles de rivières, Extraction de sable, Facteurs anthropiques, Pression urbaine, Résilience, Sensibilité géomorphologique.

ABSTRACT

Understanding river response to external controls and its geomorphic sensitivity is critical for planning sustainable management strategies. The Yamuna River with 1,376 km length and 366,223 km² basin area is a key Himalayan river supporting 341,628 number of people for their agriculture, industry, and urban needs. This study integrates geomorphic characterization, stream power analysis, hydrological modeling, and remote sensing to assess its response to projected climate scenarios and anthropogenic influences. Geomorphic analysis was carried out using the River Styles framework and segmentation analysis of river channel using the Fluvial Corridor Toolkit.

Geomorphic attributes for River Styles were analyzed across spatial scales and were used to classify the river system in thirteen different geomorphic classes. Stream power distributions were derived from historical hydrological records and DEM derived longitudinal profile. Future hydrological scenarios were simulated via the Variable Infiltration Capacity (VIC) semi-distributed hydrological model driven by INM-CM5-0 and MIROC6 climate models. Results reveal spatial variability in climate change impacts, classifying river reaches into sensitive and resilient zones. Reach-scale sensitivity map of the Yamuna River system will provide a fundamental dataset to priorities the stream management efforts.

Further, 460 km long channel reach from mountain front to downstream of Delhi megacity was analysed with high-resolution (500 m) segmentation of the river using the Fluvial Corridor Toolkit to understand anthropogenic impacts on river channel. Key geomorphic parameters including channel width, braiding index, water width, and vegetation width were quantified for each segment. Results highlight extensive human-induced modifications. Anthropogenic influences, particularly in the alluvial reaches, have surpassed climatic and geological controls, driving geomorphic transformations. Notably, sand mining, dam construction, and encroachment in the Delhi megacity urban corridor have disrupted natural fluvial dynamics.

This multi-scale multidisciplinary study highlights the integration of climate, and anthropogenic drivers that shape Yamuna's contemporary morphology and its future trajectory. The results provide new insight for integrated, multi-scale management strategies. Synthesizing climate projections, hydrological simulations, and geomorphic analyses provide a comprehensive assessment of evolving fluvial dynamics, advocating for proactive interventions to mitigate human-induced disturbances and preserve riverine functionality under escalating environmental pressures.

Keywords- **Anthropogenic driver, Barrages, Climate change, Geomorphic sensitivity, Resilience, , River Styles classification, Sand mining, Urban Pressure**.

1. INTRODUCTION

River corridors are inherently complex, dynamic, and interconnected social-ecological systems that sustain both the material and cultural dimensions of human life (Dunham et al., 2018; Hand et al., 2019). Historically, they have supported human settlements, agriculture, commerce, and industry (Ward, 1978; Kumar et al., 2019). However, in recent decades, the combined pressures of rapid urbanization, population growth, and intensive land-use changes have resulted in widespread degradation of riverine environments (Macdonald, 1999; Pielou, 1998). These impacts are further amplified by climatic extremes, which together threaten the ecological integrity and resilience of river systems.

The morphology of river channels is governed by a complex interplay between natural factors such as climate variability and catchment characteristics, and anthropogenic disturbances, notably the construction of dams and the extraction of riverbed sediments. Climate change exerts a significant influence on river systems by altering temperature and precipitation regimes (Konapala et al., 2020; Sharma & Goyal, 2020), which subsequently affect hydrological processes like evapotranspiration and runoff (Raihan et al., 2021; Yifru et al., 2021). These alterations impact flood regimes (Knox, 2000; Loukas et al., 2004), sediment dynamics (Coulthard & Macklin, 2001; Cox et al., 2021), and ultimately, channel form and behavior (Lotsari et al., 2015). Recently, future hydrological scenario in response to climate change has been generated for various river system (Mishra et al., 2016) but there are limited work to assess future geomorphic state of river system and its sensitivity to climate change.

Simultaneously, large-scale infrastructure projects such as dams disrupt longitudinal continuity by modifying discharge and sediment connectivity between upstream and downstream reaches (Wohl, 2017). Industrial-scale sand mining further intensifies morphological instability by creating sediment deficits—removing more material than the river can naturally replenish—which can lead to bed incision, bank erosion, thalweg shifts, and significant changes in channel planform (Collins & Dunne, 1990; Sear & Archer, 1998; Barman et al., 2019; Hackney et al., 2021; Quick et al., 2025). These cascading effects highlight the need to disentangle and assess the coupled impacts of climate variability and human interventions on river morphodynamics.

To address these complexities, this study employs the **River Styles Framework and River Segmentation** to classify and assess the geomorphic condition of the Yamuna River, India's longest tributary of the Ganga River. Originating at an elevation of 6,325 meters in the Higher Himalayas, the 1,376 km long Yamuna River drains an area of approximately 345,000 km² and traverses diverse physiographic settings, from steep mountain valleys to the alluvial plains, supporting several major urban centers, including the Delhi National Capital Region. Given its strategic socio-environmental significance, understanding the Yamuna's response to external pressures is critical for future river management.

This research involves a twofold approach. First, the River Styles method is applied along the entire 1,376 km length of the river to delineate geomorphic reaches based on physical form and behavior. Second, a detailed reach-based segmentation over a 460 km stretch is conducted to quantify human-induced disturbances, such as the presence of barrages, intensity of sand mining, and urbanization pressure from megacities. This study uncovers the spatial heterogeneity in river response patterns by comparing geomorphic sensitivity with local-scale controls, including geology, tectonic activity, tributary confluences, and anthropogenic controls.

Our findings underscore the need for reach-scale analysis to capture the nuanced interplay between climate change and human interventions. This integrated framework advances the understanding of the Yamuna's morphodynamic evolution and offers a transferable approach for assessing and managing other river systems across the Himalayan region under future climate and development scenarios.

2. STUDY AREA AND METHODOLOGY

The Yamuna River, originating from the Yamunotri Glacier and 3.19% (11,700 km²) of its basin area, comprises hilly terrain above 600 m, 44% (161,231 km²) consists of foothills and plateaus at altitudes of 600–300 m, and 47.22% (172,917 km²) is plains and valleys with elevations of 300–100 m (Kumar et al., 2018). The plains, dominated by alluvial soil, cover 42% of the basin. The Yamuna basin represents 42.5% of the Ganga basin and 10.7% of India's land area (Kumar et al., 2018). While Delhi has the highest population density in the basin (43% of habitation), it occupies only 0.4% of the Yamuna's catchment area (Kumar et al., 2018).

We employed the River Styles Framework (Brierley; Fryris, 2005) to classify geomorphic reaches along the Yamuna River and assess their sensitivity to climate and anthropogenic pressures. Landscape settings, valley confinement, and channel morphology were delineated using Landsat imagery and SRTM DEM, with planform and floodplain features adapted from Bawa et al. (2014). Hydraulic parameters were measured in the field using ADCP, while 20 years of discharge data from the CWC informed stream power analyses. Sediment samples were analyzed using a Mastersizer 3000 to derive d_{50} values. Future discharge scenarios were simulated using the VIC model, calibrated for the Yamuna basin and coupled with VIC-routing, incorporating ensemble means from two CMIP6 GCMs (INM-CM5-0 and MIROC6).

Fluvial geomorphological metrics including channel width, vegetation width, water width and braiding index were extracted from Landsat (1989–2024) using the Fluvial Corridor Toolbox. This toolbox segmented the reach into 500m length of segments and for each segment geomorphological metrics were extracted, enabling a multi-scalar and high resolution assessment of geomorphic responses to climatic and human drivers.

3. RESULTS AND DISCUSSIONS

3.1 Riverstyle Classification

The Yamuna River is classified into three landscape units (Himalayan upland, alluvial fill and badlands), and three valley settings (confined, partly confined and laterally unconfined). It is categorized into thirteen different River Styles on the basis of hierarchical river features including landscape units, valley confinement, channel planform, geomorphic units and sediment grain size. There are a total of four River Styles in the confined valley setting, three in partly confined valley settings and six in laterally unconfined valley settings. The River Styles of the river is controlled by both natural and anthropogenic factors. The natural factors responsible for the change are tectonics, lithology, and tributary confluence. While the anthropogenic factors like barrage construction and urban centre also seems to be a major control on the river.

The driving force for geomorphic variability was analysed using the total and specific stream power distribution patterns. Total stream power and specific stream power values for the current year (2024) is compared with the projected stream power values of the years 2050 and 2100. However, stream power variation is significantly different across the reaches.. An increasing trend is observed in the stream power values, with the range (4-480) %. The current specific stream power distribution across the river style reaches was used to define threshold values for each river style.

We classified the river into resilient and sensitive reaches on the basis of change in stream power and its variation across the threshold value for other river styles. We identified seven reaches as 'resilient', six as 'sensitive', and two as 'sensitive to tributary' reaches for future climate change scenario. Pattern of geomorphic sensitivity remains similar in response to 2050 and 2100 future climate data, tough magnitude changes in different scenarios. Resilient reaches are expected to stay stable, while sensitive reaches are likely to undergo channel transformation.

3.2 River Segmentation

3.2.1 Anthropogenic Impacts in the Upstream of Delhi National Capital Region(NCR)

The river reach is significantly influenced by a barrage located 45 km downstream of mountain front. Further, downstream of barrage is affected by extensive sand mining activities. These impacts are most evident in the reduction of the river's active channel width, particularly within 85 km downstream of the dam. However, the influence on water width remains minimal. The geomorphological context also plays a critical role in this channel narrowing, as it is absent within the gravel-bed braided channel reach extending 25 km downstream of the dam. Beyond this reach, the active channel width gradually decreases, accompanied by a slight increase in water width. This combination promotes the stabilization and exposure of bars, as reflected in the consistent increase in vegetation width throughout the reach, indicating enhanced stabilization of sand bars.

3.2.2 Effect of Delhi Megacity

Delhi NCR exerts significant pressure on the river channel, amplifying the impacts of upstream anthropogenic disturbances. The channel width experiences a marked reduction, accompanied by a decline in water width in the upstream sections near Delhi. Additionally, embankments on both riverbanks have constrained the channel, contributing to the river's progressively drying state with in increase in vegetation area. The observed scattering and downstream irregular patterns in morphologial indices indicate localized sand mining activities, which intensify closer to Delhi, further disrupting the system. However, 35 km downstream from Delhi NCR the Hindon River, a tributary, confluences with the Yamuna, resulting in a partial recovery of both channel and water width, suggesting imrovement in hydrological and geomorphological stabilization in this reach.

Our study indicates that the Yamuna River is influenced by both climate and anthropogenic controlsin which anthropogenic pressures become increasingly significant as the river approaches urban areas. Additionally, the meandering sections of the river are observed to be more sensitive to external stressors compared to the relatively resilient braided reaches, highlighting varying responses to environmental and human-induced impacts along different morphlogical zones.

4. CONCLUSION

Our study demonstrates that river reaches exhibit distinct geomorphic responses to climate change, emphasizing the inadequacy of broad, basin-scale approaches for effective river management. Instead, reach-scale analysis offers a more precise understanding of river dynamics, enabling targeted interventions. To facilitate this, we introduced a novel reach-scale river classification framework, providing a practical tool for developing context-specific management strategies.

River segmentation results reveal that the combined impacts of sand mining, dam regulation, and urban pressures especially in megacity-adjacent reaches intensify alterations in channel morphology, disrupt hydrological regimes, and compromise ecological integrity. These compounded stressors underscore the urgency of implementing sustainable, reach-specific management strategies.

Ultimately, our findings call for an interdisciplinary, reach-scale approach that prioritizes the mitigation of anthropogenic pressures and climatic extremes, and emphasizes on the enhancement of ecological resilience, ensuring the long-term health and functionality of river systems like the Yamuna and others across the Himalayan region.

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